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EVALUATION OF THE POTENTIAL FOR EXPANSION & CRACKING DUE TO THE ALKALI-CARBONATE REACTION

EVALUATION OF THE POTENTIAL FOR EXPANSION AND CRACKING DUE TO THE ALKALI-CARBONATE REACTION

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EVALUATION OF THE POTENTIAL FOR EXPANSION AND CRACKING DUE TO THE ALKALI-CARBONATE REACTION

SUMMARY

Alkali-carbonate reactive rock was inadvertently used in the Cornwall and Ottawa areas of Ontario between 1978 and 1982. The excessive expansion and cracking caused by this reaction has resulted in the need to replace concrete within 3 years of construction. In other cases, expensive remedial work has been undertaken in an effort to lengthen the serviceable life of concrete. This reaction of dolomitic limestone with the alkalies from cement is well known in the Orillia-Kingston areas of Ontario. It had not previously been expected in the Cornwall and Ottawa areas.

In an effort to prevent further occurrences of this reaction, 17 quarries in the Gull River Formation of Black River age have been studied. Aggregate durability tests, chemical analysis and concrete prism expansion tests were conducted on 26 bulk aggregate samples. Concrete prism expansion tests were conducted at alkali contents of 1.25% and 3.0% Na_2O equivalent. Chemical analysis and the rock cylinder expansion test were conducted on 122 hand specimens from various quarries.

Results have shown that the current Canadian Standards Association and Ministry of Transportation and Communications specifications are inadequate for recognizing some alkali-carbonate reactive aggregates. This was due to the occurrence of delayed expansive aggregate. It is recommended that the concrete prism expansion test be conducted using cement with an alkali content of 1.25% Na_2O. Those aggregates that exceed 0.025% expansion at 1 year should not be used in highway structures exposed to de-icing salt.

A rapid chemical screening test is proposed. The determination of the CaO:MgO ratio and alumina content or insoluble residue can be used to effectively screen potentially alkali-carbonate expansive rocks from those that are non-expansive. Those that are potentially expansive should then be tested in the concrete prism expansion test.

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EVALUATION OF THE POTENTIAL FOR EXPANSION AND CRACKING DUE TO THE ALKALI-CARBONATE REACTION

INTRODUCTION

The expansion of carbonate rocks in portland cement concrete and the associated cracking is known as the alkali-carbonate reaction. The effects of this reaction were first described by Swenson in 1957. Since then over 100 papers have been published which are related to this problem (Rogers and Worton, 1985). Over the past ten years there has been a reduction in interest in this reaction, few papers having been published. In Ontario, extensive testing had been carried out in the 1960's and early 1970's (Smith, 1964; Smith, 1974; Ryell et al, 1974). The quarries containing reactive aggregate had been identified and restrictions placed on the use of this aggregate with portland cement. It was thought that the problem was under control.

In 1981, spectacular expansion and deterioration was caused by a alkali-carbonate reactive aggregate from a quarry in Cornwall, Ontario (Figures 1 and 2). Expansions of about 1 percent were recorded in concrete sidewalk and curb and gutter after 3 years exposure. This expansion resulted in compressive failures, blow ups, shoving of adjacent asphalt pavement and other associated damage. The quarry which supplied the coarse aggregate is over 160 km from the Pittsburg quarry in Kingston, where this reaction was first recognized and described. The rock quarried in Cornwall is called the Ottawa limestone, that in Kingston is called the Gull River Formation (sometimes known as the Lower Black River). The two quarries are located in different sedimentary basins separated by a Precambrian high called the Frontenac Arch (Figure 3).

Examination and study of the reactive rock in Cornwall showed that it was identical in petrography, properties and geological age to that encountered near Kingston. Local engineers had been misled as to the potential reactivity of the rock in Cornwall because of the different geologic names applied to the strata. They had assumed, with some justification, that the rock in Cornwall was unlikely to be alkali-reactive because it was called Ottawa limestone and not the Gull River Formation which was known to be potentially reactive. Subsequent investigation revealed that another quarry operation, near Ottawa, had started to extract and use alkali-carbonate reactive rock.

Clearly the impetus of investigation conducted in the 1950's and 1960's had not been maintained. In 1982 a program of testing and pre-qualification of all concrete aggregate sources was started.

This report describes some of the results of this testing and uses this data to make suggestions for modifications to the current acceptance procedures.

SAMPLE COLLECTION

Every quarry in Ontario located in the Gull River Formation and Ottawa limestone that was supplying or intended to supply concrete aggregates was visited. The face of each quarry was logged in detail. In some quarries detailed sampling was conducted on a bed by bed basis. In all quarries, the operator was asked to make a stockpile of aggregate from the elevations or levels in the quarry that he wished to have considered for approval. A sample of about 150 kg was taken from each stockpile.

LABORATORY TESTING

In study of the expansivity of potentially alkali-carbonate rock the following tests are currently used in Ontario: The rock cylinder expansion test (ASTM C586) and the concrete prism expansion test (CAN3-A23.2-M77). The rock cylinder test is sometimes used in preliminary investigation of potential concrete aggregate sources to identify expansive beds and horizons. The concrete prism expansion test is used to determine whether or not the expansivity due to the reaction, if present, is deleterious.

Hand Samples

Hand samples taken during detailed logging of some quarries were tested in the rock cylinder expansion test (ASTM C586). The procedure was varied slightly. Flat ends rather than conical ends were used. The flat ends were made using a miniature lathe. The use of a lathe ensures that the end faces are parallel to each other and perpendicular to the long axis of the cylinder. Flat ends have been found easier to make and more reliable to measure than the conical ends recommended in the test procedure. Thin sections were made and chemical analysis and acid insoluble residue determinations conducted. Chemical analysis for the major elements was done by X-ray fluorescence using the following calibration standards: National Bureau of Standards Reference Materials, IC and 88A. The acid insoluble residue in hot 10% HCL was determined on 10g specimens of representative bulk samples crushed to pass the 75 um sieve. Results are shown in Tables 1, 2 and 3.

Aggregate Samples

All samples were oven dried, graded and submitted to aggregate durability tests. Chemical analysis and acid insoluble residue determinations were conducted on representative samples. Results are shown in Tables 4 and 5.

The aggregate tests conducted were: The magnesium sulphate soundness test (MTC LS 606); the Los Angeles abrasion and impact test (MTC LS 603); the determination of absorption and bulk, dry, relative density (MTC LS 604); the determination of Petrographic Number (MTC LS 609) and the resistance to freezing and thawing (MTC LS 614). The latter two tests are unique to Ontario.

To determine Petrographic Number, petrographic examination is conducted on a representative sample of aggregate. The particles are categorized as to their rock type and quality. Quality is determined by such attributes as: porosity, strength and argillaceous impurities. Four quality categories are recognized: Good, fair, poor and deleterious. The weight percent of material in any category is multiplied by the factor 1 for good aggregate, 3 for fair, 6 for poor and 10 for deleterious. The sum of the products is totalled to arrive at a Petrographic Number (PN). An aggregate with a PN of 100 is composed of 100% good aggregate, an aggregate with a PN of 1000 is composed of 100% deleterious aggregate. The maximum PN allowed for use in structural concrete is 140.

The freeze-thaw test is currently under development and evaluation prior to routine use. A sample of aggregate is sieved to refusal on a specified screen. The sample is placed in a 1 litre jar and immersed in 3% sodium chloride solution for 24 hours. The sample is then drained and the jar sealed. The jar and saturated sample is then submitted to five cycles of freezing and thawing. The sample is then oven dried, sieved on the original screen and the loss expressed as a percentage of the original weight.

Following aggregate testing, the concrete prism expansion test was conducted. The method described by the Canadian Standards Association (C.S.A.) (CAN3-A23.2-M77, 1977) was generally followed. 75x75x400 mm prisms were used with coarse aggregate proportioned as follows:

40% of 19.0 mm - 13.2 mm:
30% of 13.2 mm - 9.5 mm:
30% of 9.5 mm - 4.75 mm:

Control prisms were made and tested using known non-reactive aggregate. As a further control measure, aggregates of known reactive properties from the original Pittsburg quarry in Kingston were also tested.

One set of prisms was made with a normal cement of about 0.9% Na_2O equivalent alkali, with the alkali content raised to 1.25% Na_2O by addition of NaOH to the mix water. Another set of prisms were made at 3.0% Na_2O. The test procedure specifies a mix containing 310 kg/m^3 of cement. In Ministry of Transportation and Communications (M.T.C.) construction practice this would represent a 20 MPa mix. A cement with 1.25% Na_2O in a mix of 310 kg/m^3 corresponds to a concrete alkali content of 3.9 kg/m^3 Na_2O equivalent. The maximum cement content normally encountered in Ontario highway practice is about 415 kg/m^3 for 35 MPa or greater strengths of concrete. A level of 3.9 kg/m^3 of Na_2O will be given to a 415 kg/m^3 mix by a 0.93% Na_2O equivalent cement. Given the high alkali content of normal Ontario cements (0.8 - 1.2% Na_2O), it can be seen that the addition of NaOH to the mix is not unrealistic for modelling the effect of the high cement contents that are often used. The artificially high soluble alkali content also balances to some extent the effect of the addition of sodium chloride from deicing salt, causing an increase in reaction and expansion. This effect is well documented for both the alkali-silica reaction (Stanton et al, 1942; Chatterji, 1978 and Mehta, 1978) and for the alkali-carbonate reaction (Smith, 1964).

The prisms stored in the moist room, were examined periodically with the unaided eye. Cracking varied from hairline fractures at the limit of unaided resolution to wide (0.5 mm to 1.0 mm) cracks. Typically, cracking was observed when expansion exceeded about 0.03 percent.

Concrete prism expansion test results are shown in Table 6.

DISCUSSION

Concrete Prism Expansion Test

Prior to 1983 the M.T.C. specification limit for expansion in this test was 0.02% at 84 days. In 1983, following the experience in Cornwall, the maximum permitted expansion was adjusted to 0.015% at 84 days and 0.025% at 168 days. This change was made to enable recognition and rejection of some aggregates that had been found to cause objectionable cracking of concrete in a moist environment within 5 years as well as those that caused deleterious expansion in the field requiring remedial work within 2 to 3 years.

A plot of expansion at 84 and 168 days is shown graphically in Figure 4. It can be seen that there were 4 samples that met the pre-1983 M.T.C. and C.S.A. (CAN3-A23.1-M77, 1977) wet exposure criterion of 0.02% at 84 days yet continued to expand and caused cracking of prisms at about 1 year. Using the new criteria of 0.025% at 168 days, two of these 'objectionable' aggregates were rejected. There were however, two aggregates that met the 168 day requirement but continued to expand and caused cracking at 1 year (Figure 5). These aggregates could be called 'delayed expanders'. They did not have the properties of the 'late-expansive' rocks described by Dolar-Mantuani (1971).

The judgement as to whether or not cracking of these delayed expansive-prisms is objectionable, is a subjective one. This is, however, a highly important decision since it determines possible revisions to acceptance criteria. Fortunately, the two aggregates have some field performance record. Both aggregates have caused cracking of highway structures or precast concrete exposed to a highway environment. The cracking, while unsightly, has not directly caused rapid deterioration or an immediate need to replace or repair the structural element. The aggregates may be thought of as being at the boundary between undoubtedly good aggregate on the one hand and definitely poor aggregate on the other. These two aggregates are in a grey area where a subjective decision about suitability must be made. In order to decide whether or not to accept these borderline aggregates, a brief examination of the economics of the use of aggregate in highway structures is required.

The high costs of rehabilitation of bridges due to corrosion of steel are well known (Ryell et al, 1984, Fitzpatrick et al, 1981). In an effort to reduce these future maintenance costs, M.T.C. has adopted a policy of providing positive protection to new structures. The steps taken include: the use of epoxy coated steel reinforcement, increases in the thicknesses of deck slabs to increase concrete cover and the use of higher strength concrete in some parts of the substructure. These measures have increased the cost of construction of a typical 3 span highway structure by 8.5% (Ryell et al, 1984). In the example chosen by Ryell et al, the cost of the concrete aggregate represented about 1% of the total cost of the structure.

Since the value of the aggregates used in a typical highway structure is such a small proportion of the total cost there is nothing to be gained by using a borderline aggregate if other more suitable aggregates are available. By increasing the cost of a typical structure by 8.5% through providing positive protection, it is clear that M.T.C. is committed to improving long term durability and reducing future maintenance costs. As a result, in view of the aggregates' small contribution to the overall cost of the structure, the aggregate should be of impeccable quality. The gain by using a possibly, slightly cheaper aggregate that may cause cracking does not compare with the risk to the long term performance of the structure. Cracked concrete may serve for many years. Uncracked concrete will last a lot longer.

As a result of the argument above, specifications should be conservative to ensure that only the best quality aggregate is used in highway structures. This argument does not necessarily apply to many other uses of aggregate such as in mass concrete or concrete pavement. In these cases, the cost of the aggregate and haulage may play a major part in determining the final cost of the completed construction. In granular base, for instance, the use of marginal aggregates may give significant cost advantages without necessarily affecting the expected life or maintenance costs of the highway. Marginal aggregates should not be used in concrete for highway structures. There is little or no economic advantage to be gained with considerable risk to the maintenance free and overall life of the structure.

As a result of these arguments it is proposed that aggregates that cause cracking of concrete in the field at any age or in the laboratory at 1 year should not be used. It remains to choose an effective procedure for recognizing these aggregates.

Proposed Limits for Concrete Prism Test

Figure 6 shows a plot of expansion of prisms made with 3.0% Na_2O at 84 days and 1.25% Na_2O at 1 year. It can be seen that the use of 3.0% Na_2O accelerates the rate of expansion. Points fall on either side of a 45° line showing that, on average, expansion in 3.0% Na_2O cement at 3 months is about the same as expansion in 1.25% Na_2O cement at 1 year. Since 1.25% Na_2O cement more closely represents the actual alkali content encountered in the field, these results at 1 year should be the ones that are most significant for setting a specification.

Waiting a year to make a decision on the acceptability of an aggregate is viewed by many engineers as unreasonable and unwarranted. There is a need for a procedure for the rapid acceptance of most aggregates, with only those with a high chance of rejection being tested to 1 year.

The following specification requirements are suggested:

> An aggregate may be accepted if concrete prisms made with 3.0% Na_2O equivalent cement do not exceed 0.01% expansion at 84 days. If the 84 day expansion requirement is exceeded, the expansion in 1.25% Na_2O equivalent cement should not exceed 0.025% at 1 year.

Figure 6 shows that the use of a maximum expansion criteria of 0.01% at 84 days in 3.0% Na_2O would have resulted in acceptance of 12 or 46% of the aggregates tested in this program. It would have been necessary for 14 or 54% of the aggregates to be tested to 1 year. After 1 year, seven aggregates (27%) would have been accepted and seven aggregates (27%) would have been rejected.

It must be emphasised that the 84 day criteria should not be used to reject aggregate, it is only used to accept material. If the 84 day criterion is not met, then the test of the 1.25% Na_2O prisms must be continued to 1 year before a final decision is made.

Table 7 shows a summary of various maximum acceptable expansion criteria for this test from the published literature. It will be seen that the proposed maximum expansion of 0.025% at 1 year is similar to the 0.03% value recommended by Newlon et al (1972b) and a proposed ASTM limit reported by Walker (1978). Ryell et al (1974) in their study of the Uhthoff quarry concluded that the Newlon et al (1972b) 1 year criterion was more effective at identifying expansive rocks than the then current M.T.C. requirement of 0.02% at 84 days. In this present study a value of 0.03% might have been chosen but for the occurrence of a sample that gave 0.029% expansion, cracked, and is also known to cause cracking in the field. Since the intention, for reasons already stated, is to select a conservative specification, a value of 0.025% at 1 year is suggested.

Pittsburg Control Specimens

This is the quarry whose aggregate was first recognized as being alkali-carbonate reactive (Swenson, 1957). The first lift (0-24') is often used as a standard alkali-carbonate reactive aggregate. Samples were taken from the 1st and 3rd lifts (Sample No's 82-40026 and 27 respectively). The concrete prism expansion data for these samples is shown in Table 9 together with the results of testing reported in earlier studies.

Considering the variation in alkali contents, test equipment and procedures over the past twenty years and the difficulty of sampling the identical horizons in 1982 to those used from 1957 onwards, the data show reasonable consistency.

Quick Chemical Screening Test

Researchers have long recognized that the majority of expansive alkali-carbonate reactive rocks are dolomitic limestones of moderate to high clay content (Swenson and Gillott, 1960; Hadley, 1961; Newlon and Sherwood, 1962; Dolar-Mantuani, 1964; Hadley, 1964; Sherwood and Newlon, 1964; Swenson and Gillott, 1964; Newlon et al, 1972a; and Ryell et al, 1974). Clay content has usually been determined by an acid insoluble residue analysis. In such an analysis, quartz contributes to the insoluble residue making it difficult to determine the actual clay content. In Ontario, the alkali expansive rocks contain significant amounts of insoluble silica, as quartz, (See Table 8) and other insoluble, detrital or authigenic minerals such as pyrite.

In carbonate rocks, the clays are the only minerals present in any significant quantity to contribute alumina (Al_2O_3) to a chemical analysis. Detrital and authigenic feldspars may also contribute alumina to the analysis. In thin sections of the rocks tested in this study, detrital and authigenic feldspars were observed in 3 samples out of several hundred thin sections. The amount of feldspar in these samples was less than 1%. The contribution of alumina by feldspar in chemical analysis can be ignored for practical purposes. The alumina content should be a good quantitative measure of the clay content of sedimentary carbonate rocks. Lamar (1967) advocated the use of alumina content, multiplied by a suitable factor, to determine the clay content of sedimentary carbonates. Baxter and Harvey (1969) found that clays were the only alumina-bearing minerals they observed in a suite of sedimentary carbonate rocks. They considered that alumina indicated the relative amount of clay in their samples.

In Figure 7, a plot of CaO:MgO ratio versus Al_2O_3 content is shown. It can be seen that all deleteriously expansive rocks fall in a distinct field. Deleteriously expansive rocks were considered to be those that gave rock cylinder expansions (ASTM C586) that exceeded 0.1% at 4 weeks or 0.2% at 16 weeks, and concrete prism expansions (CAN3-A23.2-M77) in excess of 0.025% at 1 year. A number of unreported analyses of known non-reactive and commonly used, concrete aggregates are also plotted.

In Ontario, it has been found that all quarry faces (sampled at about 0.3 m intervals, n= 8 to 16) which gave average rock cylinder expansions of greater than 0.1% at 4 weeks also caused excessive expansion and cracking when used in concrete. It should be noted, however, that there have been two examples where average expansions of less than 0.1% at 4 weeks were obtained yet the expansion at 1 year in the concrete prism expansion test was excessive (82-40027 and 82-40031). In the case of sample 82-40027, there was a slight average contraction of rock cylinders at 4 weeks and an average expansion of 0.07% at 1 year. In the case of sample 82-40031, the average expansion at 16 weeks was 0.31% and 0.51% at 1 year. In addition, examples have occurred where rock cylinder expansion in excess of 1% has been recorded yet the aggregate is not considered alkali-carbonate reactive. This phenomenon may be due to swelling associated with sodium ion exchange in a mixed layer illite/montmorillonite clay present in small quantities in argillaceous limestones. Thus the rock cylinder expansion test is not totally reliable at predicting likely expansivity of portland cement concrete due to the alkali-carbonate reaction. Nevertheless, the value of 0.1% at 4 weeks was chosen as being reliable in the majority of cases. The value of 0.2% at 16 weeks is that considered 'reasonable' by Newlon et al (1972,a) to indicate potentially deleteriously reactive rock. This is also the value considered to be tolerable by Ryell et al (1974).

In Figure 8, a plot of CaO:MgO ratio versus insoluble residue is shown. The number of points differs from that in Figure 7 because of the unavailability of insoluble residue data for some samples. It can be seen that the use of either Figure 7 using alumina or Figure 8 using insoluble residue should be equally effective at screening the potentially deleterious expansive properties of aggregates from Southern Ontario. The ratio of clay to other insoluble minerals in any sedimentary basin of deposition is determined by the distance from and nature of the source of the detrital material. In other sedimentary basins which contain potentially alkali-carbonate

reactive rocks, the ratio of clay to other minerals in the insoluble residue will probably be different from that in Ontario. In other areas, the plot of CaO:MgO versus alumina (Figure 7) will probably be more useful than that using insoluble residue (Figure 8) since it is the clay minerals, represented by alumina, that are presumably associated with the expansion (see Gillott, 1975).

The boundaries in these graphs have been drawn in a conservative manner so as to include as many potentially reactive rocks as possible.It is worth noting however, that those rocks found to be most deleterious in field experience and the laboratory have a more restricted chemistry. These rocks have a CaO:MgO ratio of between 5 and 10, and an alumina content of between 2 and 3%; or an insoluble residue of between 10 and 15%. Aggregates of these chemical properties usually cause severe cracking and expansion of concrete within 2 to 3 years under moist conditions.

In Figures 7 and 8, it will be seen that a number of aggregates tested in the concrete prism expansion test, while having a CaO:MgO ratio and alumina or insoluble residue content that place them in the potentially expansive field did not give deleterious expansion after 1 year. These aggregates were mixtures of individual dolostone and limestone beds that resulted in an average composition falling in the potentially expansive field. The expansive aggregates were predominantly dolomitic limestone and were not mixtures of dolostone and limestone. If a reliable method of distinguishing individual dolostone and limestone particles were used, such as petrographic examination, the usefulness of this procedure would be improved. Petrographic examination, while a reliable technique in skilled hands, is a subjective procedure. The purpose of this study has been, as far as possible, to remove subjective elements as well as methods or skills that may not always be readily available and still arrive at a reliable and accurate method of recognizing reactive rocks. It is worth noting that the dark colour (due to disseminated sulphides) of many of these rocks makes the use of staining tests such as the Copper Nitrate test (Dolar-Mantuani, 1962) unreliable. The conventional test, observing the degree of effervescence of cold, dilute hydrochloric acid on the rock, may also be unreliable. The high insoluble residues encountered with many of these dolomitic limestones, up to 47%, reduces the amount of effervescence to the amount normally encountered with dolostones.

In future evaluation of quarried carbonate rocks, it is suggested that a representative sample be submitted to chemical analysis at the same time as routine aggregate durability testing is conducted. The results should then be plotted on either figure 7 or 8. If the sample falls in the potentially expansive field, further testing in the concrete prism expansion test (CAN3-A23.2-M77,1977) is necessary.

Suggested Evaluation Procedure

Figure 9 shows a suggested scheme for the orderly and systematic collection of data to evaluate the suitability of sedimentary carbonate rocks for use in portland cement concrete. The necessary tasks and decisions are clearly set out. It should be noted, however, that to avoid unnecessary delays the decision to test for potential alkali-silica reactivity should be made before concrete prism test data are available.

If it is anticipated that carbonate aggregate is to be used for concrete paving, consideration should be given to testing for the potential for D-line cracking. The steps to accomplish this have been omitted from the flow chart (Figure 9).

Unconfined Freeze-Thaw Testing

Figure 10 shows a plot of loss in the unconfined freeze-thaw test (MTC LS 614) against loss in the magnesium sulphate soundness test (MTC LS 606). It can be seen that the alkali-carbonate expansive aggregates generally gave satisfactory losses in the sulphate soundness test (15% or less). With one exception, the losses in the freeze-thaw test were always greater than 18%. Further work has to be done on standardizing the rate of cooling and minimum temperature in this test. Nevertheless, the test appears to show promise as a useful technique for recognizing alkali-carbonate expansive rock.

CONCLUSIONS

Testing of a suite of potentially alkali-carbonate reactive rocks from Ontario has led to the following conclusions:

1. A requirement of a maximum expansion in the concrete prism expansion test of 0.02% at 84 days did not completely separate suitable from unsuitable aggregate. Values of 0.015% at 84 days and 0.025% at 168 days were also not completely effective. This was due to the occurrence of delayed expansive aggregate.

2. A maximum expansion, in the concrete prism test with 1.25% Na_2O equivalent cement, of 0.025% at 1 year was found to be an effective limit for separating aggregates that caused cracking in the field from those that did not.

3. The testing of aggregate in 3.0% Na_2O equivalent cement did accelerate the rate of expansion. A maximum expansion of 0.01% at 84 days in 3.0% Na_2O can be used as an acceptance limit for many aggregates. Where expansion exceeds this requirement, testing should be continued to 1 year with 1.25% Na_2O equivalent cement.

4. The determination of the CaO:MgO ratio and alumina or insoluble residue content of rocks can be used to effectively screen potentially alkali-carbonate expansive aggregate samples from those that are definitely non-expansive.

5. An unconfined freeze-thaw test using 3% sodium chloride solution shows promise as a useful screening test for evaluating the potential for alkali-carbonate expansivity.

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SAMPLE NUMBER	CHEMICAL ANALYSIS									ROCK CYLINDER EXPANSION, PERCENT				
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	CO_2	L.O.I.	CaO:MgO	Insol. Res. %	4 wks.	12 wks.	16 wks.	24 wks.	32 wks.
1.1	18.8	6.27	2.17	2.37	28.4	31.4	31.0	12	28	-0.03	-0.02	-0.03	-0.06	-0.08
1.2	10.9	2.37	0.58	1.22	44.4	38.1	37.9	36	13	0.02	0.07	0.07	0.09	0.13
1.3	10.0	2.39	0.78	1.46	44.1	39.5	38.2	30	12	0.04	0.21	0.27	0.35	0.45
1.4	10.5	3.52	1.16	1.50	40.5	37.6	36.8	27	16	0.04	0.17	0.22	0.32	0.36
1.5	5.18	1.70	0.78	0.85	47.9	41.6	39.8	56	7.9	0.00	0.00	0.00	0.00	-0.02
1.6	6.56	2.34	0.59	0.91	45.8	40.4	38.9	50	10	-0.04	-0.04	-0.04	-0.06	-0.09
1.7	0.71	0.26	0.16	0.38	53.8	44.7	42.8	142	1.1	-0.04	-0.05	-0.05	-0.06	-0.08
1.8	0.57	0.23	0.16	0.24	54.0	44.8	43.2	>200	1.0	-0.02	-0.03	-0.03	-0.05	-0.07
D1.8	0.55	0.22	0.16	0.27	54.1	44.8	43.1	200	-	-	-	-	-	-
2.1	16.8	5.13	1.02	1.88	33.1	32.9	33.5	18	24	0.01	0.00	0.00	0.00	-0.01
2.2	20.7	4.99	0.93	1.80	30.5	30.8	31.7	17	28	0.00	0.02	0.01	0.01	0.03
2.3	29.7	6.65	2.29	3.29	24.0	24.7	25.3	7.3	41	0.10	0.22	0.24	0.27	0.33
2.4	32.5	6.41	1.82	7.51	20.2	24.2	25.2	2.7	43	0.08	0.14	0.15	0.18	0.22
2.5	27.6	6.03	1.80	8.17	21.6	27.9	28.0	2.6	37	0.03	0.09	0.09	0.11	0.14
2.6	17.5	4.10	0.72	2.01	36.0	33.6	33.5	18	23	0.03	0.08	0.10	0.11	0.14
2.7	13.0	2.15	0.56	1.66	43.8	37.6	36.5	26	15	0.00	0.00	0.00	0.00	0.00
2.8	4.18	1.53	0.60	0.87	48.7	41.6	39.6	56	-	-0.01	-0.01	-0.01	-0.02	-0.02
2.9	6.27	2.27	0.67	3.52	46.2	40.2	39.2	13	9.0	-0.03	0.03	-0.04	-0.05	-0.06
2.10	5.58	1.93	0.52	0.96	47.3	40.4	39.4	49	9.4	-0.03	0.02	-0.02	-0.02	-0.04
D2.10	5.59	1.93	0.51	0.97	47.3	40.6	39.4	49	-	-	-	-	-	-
2.11	26.7	5.75	1.93	9.41	22.5	28.8	29.4	2.4	35	-	-	-	-	-
3.1	7.20	2.52	0.58	3.52	42.5	40.7	40.0	12	8.7	0.19	0.56[1]	CB	CB	CB
3.2	4.22	1.25	0.45	1.93	48.3	42.2	41.3	25	5.6	-	-	-	-	-
3.3	6.18	2.07	0.82	8.27	38.0	41.4	41.1	4.6	8.6	0.13	0.29	0.32	0.36	0.46
3.4	11.6	3.57	1.15	5.47	34.9	37.4	37.3	6.4	17	0.94	6.23[1]	CB	CB	CB
3.5	7.63	2.41	0.73	4.46	41.2	40.5	39.6	9.2	11	0.11	0.42	0.81	1.04	2.01
3.6	5.49	1.83	0.49	2.12	45.5	40.8	40.3	21	8.1	0.02	0.06	0.08	0.10	0.22
3.7	2.37	0.79	0.43	1.17	50.9	43.1	41.9	44	4.1	-0.01	-0.02	-0.02	-0.01	-0.03
3.8	12.2	3.61	0.81	2.40	38.5	35.9	36.3	16	15	0.14	0.42	0.51	0.62	0.77
3.9	12.4	3.44	0.60	1.46	40.3	36.8	36.5	28	16	0.00	-0.01	0.00	0.00	-0.03
3.10	2.15	0.55	0.48	1.87	50.7	43.0	41.7	27	3.6	-0.01	-0.02	0.02	0.00	-0.02
3.11	44.0	7.68	2.08	6.64	14.1	18.6	19.7	2.1	55	0.00	0.00	0.00	0.01	-0.01
3.12	13.8	3.05	1.87	16.5	33.5	28.0	28.0	2.0	37	0.01	0.10	0.13	0.20	0.32
3.13	5.96	2.82	0.40	1.22	46.8	38.6	38.7	38	10	0.01	0.02	0.02	0.02	0.02
D3.13	6.01	1.78	0.40	1.19	46.8	38.6	38.9	39	-	-	-	-	-	-
4.1	12.6	2.61	1.75	14.8	24.8	39.4	38.4	1.7	15	0.00	0.00	0.00	0.01	0.01
D4.1	12.10	2.63	1.64	14.7	24.8	38.4	38.8	1.7	15	-	-	-	-	-
4.2	7.51	1.49	0.50	6.13	40.6	40.6	39.9	6.6	11	0.01	0.04	0.05	0.07	0.14
4.3	2.79	0.77	0.69	7.75	42.6	43.7	42.4	5.5	4.3	0.00	0.00	0.01	0.02	0.04
4.4	33.4	6.65	1.77	5.51	21.1	23.2	24.9	3.8	44	0.03	0.07	0.09	0.14	0.31
4.5	18.7	4.28	1.38	8.00	26.7	33.8	33.3	3.3	25	0.12[2]	0.36	0.49	0.60	0.76
4.6	15.6	4.22	1.35	4.64	32.6	35.7	34.8	7.0	21	0.77	2.26	3.47	CB	CB
4.7	21.9	6.25	1.64	7.46	23.4	30.2	30.7	3.1	31	0.64	1.01	1.37	CB	CB
4.8	15.4	3.72	1.05	6.18	32.1	36.0	35.4	5.2	19	0.61	2.23	2.83	3.45	3.69
4.9	16.5	4.73	1.48	5.12	39.2	33.7	33.4	5.7	25	1.02	CB	CB	CB	CB
4.10	8.77	2.77	1.01	5.57	37.8	38.6	38.0	6.8	13	0.06	0.26	0.38	0.54	0.69
4.11	11.7	3.13	0.80	3.57	38.6	37.5	36.8	11	15	0.15	0.64	0.93	1.31	1.94
4.12	1.92	0.50	0.32	0.75	51.0	42.8	41.7	68	3.3	0.00	-0.01	-0.01	-0.01	-0.01
D4.12	1.90	0.50	0.32	0.77	50.8	42.2	41.3	66	3.0	-	-	-	-	-
4.13	5.68	2.10	0.68	4.52	43.0	41.0	40.3	9.5	7.9	0.04	0.12	0.17	0.23	0.32
4.14	1.31	0.40	0.37	1.69	51.6	44.1	42.5	31	2.1	0.00	0.00	0.00	0.02	-0.01
4.15	1.91	0.46	0.35	1.15	51.7	43.9	42.0	45	2.7	0.00	-0.01	-0.01	-0.01	-0.01

NOTE: CB = Cylinder broke due to excessive expansion
1 = Cylinder broken, reading @ 8 weeks
2 = Cylinders cut parallel to bedding
Insol. Res. = Insoluble Residue
D = Duplicate analysis

TABLE 1. Chemical analysis and rock cylinder expansion test results of hand specimens from McLeod Quarry.

SAMPLE NUMBER	CHEMICAL ANALYSIS									ROCK CYLINDER EXPANSION, PERCENT				
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	CO_2	L.O.I.	CaO:MgO	Insol. Res. %	4 wks.	12 wks.	16 wks.	24 wks.	52 wks.
P.1	9.20	2.26	0.68	6.10	36.8	39.6	38.7	6.0	13	0.24	CB	CB	CB	CB
P.1D	9.24	2.21	0.69	6.13	36.9	39.2	38.7	6.0	10	-	-	-	-	-
P.2	7.74	1.92	0.47	1.73	44.3	39.7	38.6	26	11	-0.02	-0.02	-0.02	0.00	0.02
P.3	9.09	2.51	0.59	2.62	41.9	39.3	38.6	16	13	0.34[2]	1.00	1.10	1.15	1.15
P.4	1.98	0.59	0.28	0.67	52.8	41.7	42.5	79	2.7	-0.04[2]	-0.05	-0.06	-0.06	-0.06
P.5	1.02	0.21	0.20	0.64	53.9	44.6	43.0	84	1.7	-0.05	-0.06	-0.07	-0.08	-0.09
P.6	26.4	8.94	2.92	11.5	17.2	26.3	27.6	1.5	42	-0.04	-0.04	-0.03	-0.04	-0.02
P.7	27.7	7.65	1.86	5.84	24.2	26.6	27.5	4.1	42	-	-	-	-	-
P.8	25.8	6.93	2.05	12.1	19.4	29.2	28.0	1.6	39	-0.02	0.00	-0.01	-0.01	0.01
P.9	18.2	4.08	1.30	13.1	24.8	36.8	36.1	1.9	21	-0.02	-0.03	-0.03	-0.04	-0.03
P.10	32.0	8.60	2.65	9.97	16.3	24.4	24.8	1.6	47	0.19[1]	CB	CB	CB	CB
P.11	17.7	4.66	0.96	12.0	25.1	37.1	36.6	2.1	21	0.25[2]	0.44	0.50	0.67	0.79
P.12	11.3	2.60	0.67	10.8	31.3	40.4	39.8	2.9	13	0.29	0.44	0.48	0.58	0.65
P.13	37.0	7.10	1.99	9.26	16.4	23.2	23.7	1.8	49	-0.03	-0.04	-0.04	-0.04	-0.03
P.14	5.54	1.18	0.45	6.67	42.5	42.3	41.3	6.4	5.0	-0.02	0.01	0.02	0.05	-0.07
P.15	9.94	3.21	0.98	12.2	29.8	41.3	39.6	2.4	13	-0.15	-0.01	0.02	0.11	0.17
P.16	3.27	0.87	0.41	7.13	43.4	45.1	43.1	6.1	4.2	-0.08	-0.06	-0.06	-0.05	-0.02
P.17	3.93	0.58	0.26	2.74	50.0	43.3	42.1	18	4.8	-0.06	-0.07	-0.07	-0.07	-0.07
P.18	15.9	4.72	1.30	15.6	23.0	37.4	36.4	1.5	22	-0.04	-0.04	-0.04	-0.05	-0.05
P.19	1.75	0.22	0.21	0.91	52.7	43.0	42.3	58	2.5	-0.05	-0.05	-0.05	-0.06	-0.06
P.20	13.9	2.69	0.68	8.62	30.7	37.8	36.4	3.6	19	0.14	0.26	0.33	0.42	0.50
P.21	2.68	0.42	0.56	6.31	46.5	44.5	42.8	7.4	3.4	-0.07	-0.09	-0.09	-0.07	-0.07
P.22	13.0	2.95	0.73	8.39	31.1	37.7	36.8	3.7	18	0.04	0.16	0.22	0.37	0.47
P.23	8.23	2.18	0.44	3.05	42.1	40.1	38.8	14	11		0.04	0.05	0.07	0.10
P.23D	8.22	2.16	0.44	2.98	42.1	39.7	38.7	14	9.2	-	-	-	-	-
P.24	4.00	0.84	0.28	1.72	50.4	42.6	41.5	29	5.3	-0.04	-0.01	-0.01	0.01	0.04
P.25	11.5	3.06	0.89	11.9	29.7	40.5	39.3	2.5	13	-0.01	-0.07	-0.07	-0.05	-0.01
P.26	7.06	1.72	0.42	2.55	44.7	40.8	40.2	18	9.0	0.07[1]	CB	CB	CB	CB
P.27	5.31	1.40	0.38	3.57	45.4	42.2	41.1	13	7.2	-0.17	-0.09	-0.07	0.00	0.05
P.28	13.2	3.63	1.22	16.1	25.2	40.4	38.7	1.6	16	-0.03	-0.06	-0.03	-0.04	-0.04
P.29	9.88	2.66	1.02	14.5	29.0	41.8	40.2	2.0	12.0	-0.09	-0.07	-0.07	-0.05	-0.01
P.30	17.2	4.76	1.44	14.7	22.2	34.9	34.4	1.5	26	-0.01	-0.01	-0.03	-0.04	-0.04
P.31	15.1	4.22	0.93	9.98	27.2	38.1	36.9	2.7	18	1.00	1.11	1.13	1.24	1.41
P.32	20.7	5.57	1.59	14.7	21.0	33.8	33.7	1.4	26	-0.01	-0.01	-0.03	-0.04	0.01
P.33	34.3	6.64	1.90	10.3	17.0	25.2	25.3	1.7	44	-0.01	-0.02	-0.02	-0.02	-0.01
P.34	10.0	2.86	0.61	4.97	37.2	39.8	37.8	7.5	13	2.52	3.36	3.56	3.72	3.77
P.35	10.8	3.00	0.82	4.49	36.4	38.6	37.3	8.1	16	2.59	3.74	4.03	4.27	4.46
P.36	12.2	3.55	0.71	3.21	35.9	37.5	36.5	11	18	0.14	0.44	0.54	0.70	0.75
P.37	4.95	1.31	0.30	1.72	48.6	43.0	41.1	28	6.7	0.07	0.29	0.36	0.49	0.54
P.38	6.10	1.68	0.39	1.76	46.6	41.7	40.2	27	8.2	0.00	0.01	0.14	0.25	0.33
P.39	9.91	3.01	0.69	2.74	38.8	39.0	37.5	14	15	-	-	-	-	-
P.40	11.5	3.56	1.49	14.6	26.7	39.8	38.7	1.8	16	-0.02	-0.01	-0.01	0.00	-0.01
P.41	7.03	2.00	0.58	8.51	37.0	43.4	41.5	4.4	8.2	0.35	0.51	0.60	0.77	0.86
P.42	12.6	3.83	0.72	4.28	34.7	38.1	36.9	8.1	17	0.43[2]	1.01	1.14	1.22	1.25

NOTE: CB = Cylinder broke due to excessive expansion
1 = Cylinder broken, reading @ 3 weeks
2 = Cylinders cut parallel to bedding
Insol. Res. = Insoluble Residue
D = Duplicate analysis

TABLE 2. Chemical analysis and rock cylinder expansion test results of hand specimens from Pittsburg Quarry.

SAMPLE NUMBER	CHEMICAL ANALYSIS									ROCK CYLINDER EXPANSION, PERCENT				
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	CO_2	L.O.I.	CaO:MgO	Insol. Res. %	4 wks.	12 wks.	16 wks.	24 wks.	52 wks.
P.43	6.59	2.02	0.81	14.7	31.2	44.4	41.7	2.1	7.8	-0.07	-0.08	-0.06	-0.07	-0.07
P.44	2.12	0.29	0.32	1.45	52.1	42.5	42.1	36	3.2	-0.04	-0.05	-0.05	-0.05	-0.05
P.45	1.85	0.27	0.28	1.97	51.8	44.9	42.7	26	2.5	-0.10	-0.09	-0.09	-0.09	-0.08
P.45D	1.85	0.28	0.28	2.01	51.9	44.6	42.6	26	2.4	-	-	-	-	-
P.46	2.97	0.63	0.31	2.33	50.9	44.7	42.5	22	3.6	-0.05	-0.03	-0.03	-0.03	-0.02
P.47	2.98	0.96	0.39	8.02	42.2	45.2	43.2	5.3	3.7	0.06	0.22	0.26	0.32	0.36
P.48	5.26	1.22	0.90	16.6	31.6	46.3	43.4	1.9	5.1	-0.04	-0.05	-0.06	-0.04	-0.02
P.49	36.7	7.50	1.86	9.80	15.6	23.3	23.7	1.6	8.1	-0.02	-0.02	-0.01	-0.02	-0.01
M50	5.83	1.43	0.81	2.57	45.1	41.4	39.6	18	9.3	0.04	0.25	0.34	0.46	0.51
M50D	5.87	1.41	0.81	2.61	45.1	41.6	39.7	17	8.0	-	-	-	-	-
M51	7.75	2.19	0.63	9.27	35.0	41.8	40.7	3.8	10	0.13	0.25	0.28	0.31	0.34
M52	2.69	0.27	0.20	0.89	52.5	43.8	42.3	60	3.5	-0.06	-0.05	-0.06	-0.06	-0.06
M53	3.03	0.50	0.27	4.14	48.6	41.2	42.7	12	3.7	-0.05	-0.02	-0.01	0.02	0.06
M54	1.92	0.40	0.26	4.39	49.9	45.6	43.7	11	2.4	-0.03	-0.02	-0.03	-0.01	0.02
M56	5.87	1.77	0.59	4.73	42.4	42.7	40.6	9.0	8.1	0.12[2]	0.37	0.43	0.51	0.52
M57	5.57	1.62	0.56	8.51	38.3	42.8	41.5	4.5	9.3	0.04	0.25	0.34	0.46	1.00
M58	8.28	2.47	0.49	3.45	41.3	41.1	39.0	12	11	-0.04	0.14	0.19	0.29	0.32
M59	8.64	2.64	0.65	5.75	38.0	39.1	39.1	6.6	12	0.58[2]	0.71	0.76	0.86	0.89
M60	4.14	1.24	0.40	4.17	46.1	44.4	41.7	11	5.4	-0.02	-0.01	-0.01	-0.01	0.01
M61	3.85	1.09	0.39	3.50	47.3	43.7	41.8	14	5.5	0.09	0.35	0.43	0.57	0.61
M62	4.40	1.26	0.35	1.59	49.6	43.4	41.0	31	5.7	-0.07	-0.05	-0.05	-0.03	-0.02
M63	3.78	1.24	0.26	0.78	51.1	43.6	41.6	66	5.0	-0.07	-0.06	-0.07	-0.07	-0.08
M64	4.70	1.38	0.32	0.80	50.4	41.2	40.8	63	6.2	-0.01	-0.01	-0.02	-0.05	-0.05
M65	6.19	1.73	0.52	5.96	40.7	43.3	40.7	6.8	6.3	0.29	0.61	0.71	0.87	1.67
M66	7.55	1.54	0.48	3.07	42.8	40.6	38.3	14	13	0.08	0.16	0.17	0.22	0.24
M68	22.2	4.01	1.41	9.44	26.3	34.1	32.1	2.8	28	0.01[2]	0.01	0.03	0.04	0.10
M69	4.51	0.88	0.23	0.75	51.2	41.6	40.0	68	8.4	-0.01	-0.01	-0.02	-0.03	-0.03
M70	2.25	0.69	0.37	0.58	52.4	44.3	41.4	90	4.3	-0.07	-0.07	-0.07	-0.09	-0.10
M71	6.80	2.09	0.56	0.88	46.8	41.7	39.3	53	9.4	-0.01[2]	-0.02	-0.02	-0.03	-0.03
M72	2.74	0.90	0.28	0.86	52.0	44.6	41.8	61	4.0	-0.02	-0.02	-0.02	-0.03	-0.03
M73	2.23	0.66	0.23	0.55	52.5	43.7	42.0	96	3.5	-0.05[2]	-0.05	-0.06	-0.05	-0.04
M74	1.29	0.47	0.25	0.65	53.2	43.5	42.8	82	2.0	-0.04	-0.08	-0.11	-0.10	-0.11
M75	1.92	0.55	0.24	0.43	53.0	44.8	42.2	123	3.3	-0.01	-0.03	-0.05	-0.05	-0.06
M76	5.81	1.77	0.46	0.73	48.1	41.5	40.0	66	9.0	-0.04[2]	-0.05	-0.05	-0.05	-0.06
M76D	5.85	1.73	0.46	0.74	48.2	41.0	39.9	65	6.3	-	-	-	-	-

NOTE: CB = Cylinder broke due to excessive expansion
2 = Cylinders cut parallel to bedding
Insol. Res. = Insoluble Residue
D = Duplicate analysis

TABLE 3. Chemical analysis and rock cylinder expansion test results of hand specimens from the Pittsburg Quarry (P) and Montreal Street, Rock cut (M).

	AGGREGATE TEST					
SAMPLE NUMBER	PETRO NO.	$MgSO_4$ Percent	F/T Percent	L.A.I. Percent	ABSn Percent	REL. DEN.
81-40092	109	3	8	22	0.35	2.70
81-40093	113	3	13	20	0.50	2.70
81-40094	103	2	9	21	0.40	2.72
81-40095	102	2	20	18	0.52	2.72
81-40096	148	20	27	21	0.89	2.69
82-40003	101	2	-	23	0.27	2.70
82-40004	109	7	11	24	0.50	2.69
82-40026	117	11	31	-	0.77	2.70
82-40027	103	11	25	-	0.83	2.71
82-40028	185	47	34	-	2.69	2.61
82-40029	109	6	14	22	0.43	2.71
82-40031	105	8	19	19	1.04	2.71
82-40036	139	13	14	23	0.47	2.69
82-40037	105	2	5	22	0.50	2.72
82-40038	122	5	3	21	0.40	2.70
82-40039	159	6	5	31	0.54	2.68
82-40040	117	4	4	22	0.47	2.69
82-40042	104	3	8	22	0.44	2.69
82-40043	109	4	5	24	0.40	2.69
82-40044	115	10	3	28	0.47	2.69
82-40045	118	5	1	21	0.33	2.71
82-40046	100	6	30	20	0.97	2.68
82-40047	135	7	17	24	0.44	2.70
83-9016	135	15	27	21	1.34	2.69
83-40056	120	7	3	23	0.50	2.69
83-40062	142	13	9	24	0.54	2.69

NOTE:

PETRO NO. = Petrographic Number (MTC LS 609).
$MgSO_4$ = Magnesium Sulphate Soundness loss in percent (MTC LS 606).
F/T = Freeze-Thaw loss in percent (MTC LS 614).
L.A.I. = Los Angeles Abrasion and Impact test loss in percent (MTC LS 603).
ABSn = Absorption in percent (MTC LS 604).
REL. DEN. = Bulk, dry, relative density (MTC LS 604).

TABLE 4. Results of routine aggregate durability tests.

SAMPLE NUMBER	CHEMICAL ANALYSIS, IN PERCENT								INSOLUBLE RESIDUE PERCENT
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	CO_2	L.O.I.	CaO:MgO	
81-40092	5.12	1.79	0.45	0.82	48.2	40.5	39.0	59	9.0
81-40093	13.8	2.81	1.10	3.19	39.4	36.9	36.0	12	17
81-40094	9.15	2.63	0.72	3.99	39.9	38.3	37.6	10	14
D-40094	9.24	2.58	1.01	4.06	40.0	38.7	37.7	9.8	13
81-40095	10.07	2.82	0.78	6.14	37.0	38.9	37.7	6.0	15
D-40095	11.7	2.74	1.08	4.93	37.9	37.9	37.2	7.7	15
81-40096	19.0	2.88	1.10	5.88	32.2	34.2	33.8	5.5	24
82-40003	2.45	0.81	0.28	0.58	51.5	44.2	41.6	89	4.2
82-40004	6.41	2.04	0.56	1.03	46.4	40.0	39.1	45	9.4
82-40026	8.13	2.68	0.63	5.72	38.3	39.5	39.1	6.7	10
D-40026	8.08	2.71	0.63	5.74	38.3	38.7	39.4	6.7	-
82-40027	8.54	2.52	0.62	6.59	37.1	40.7	39.2	5.6	11
82-40028	16.8	3.80	1.32	13.1	24.4	34.0	35.0	1.9	21
82-40029	6.97	2.45	0.64	3.04	42.2	41.8	38.9	14	9.4
82-40031	8.97	3.02	0.94	9.19	32.7	40.6	39.1	3.6	12
82-40036	14.3	4.38	1.22	2.49	35.7	34.4	35.1	14	19
82-40037	4.47	0.45	0.25	1.53	51.8	41.7	41.1	34	3.7
82-40038	5.30	1.43	0.43	0.94	49.3	40.4	40.0	52	6.7
82-40039	7.28	2.19	0.47	0.18	45.9	40.6	39.2	>200	7.7
82-40040	4.02	1.15	0.31	0.62	51.8	40.8	40.5	84	5.9
82-40042	3.35	1.15	0.36	0.75	52.5	42.5	41.0	70	4.9
82-40043	4.12	1.02	0.27	0.81	51.7	40.5	40.3	64	5.4
82-40044	2.36	0.76	0.24	0.57	54.6	42.8	41.2	96	3.5
82-40045	3.03	0.91	0.28	1.34	53.4	43.4	42.1	40	2.3
82-40046	2.77	0.69	0.30	4.53	48.1	45.9	42.9	11	2.2
82-40047	6.13	2.12	0.50	1.21	46.5	40.4	39.4	38	7.8
D-40047	6.11	2.14	0.50	1.23	46.5	41.0	39.5	38	-
83-9016	4.56	1.05	0.62	8.58	38.7	44.0	41.5	4.5	-
83-40056	6.61	1.70	0.40	0.97	49.1	42.5	39.8	51	-
83-40062	6.75	1.39	0.38	0.71	48.6	37.9	39.2	69	-

NOTE: D - Duplicate Analysis.

TABLE 5. Chemical Analysis results of bulk aggregate samples.

SAMPLE NUMBER	ALKALI CONTENT Na_2O%	EXPANSION OF CONCRETE PRISMS IN PERCENT		
		84 DAYS	168 DAYS	1 YEAR
81-40092	1.25	0.011	0.014	0.014
	3.0	0.015	0.019	0.020
81-40093	1.25	0.011	0.012	0.017
	3.0	0.013	0.014	0.032
81-40094	1.25	0.014	0.028	0.032*
	3.0	0.037*	0.081*	0.119*
81-40095	1.25	0.026	0.052*	0.091*
	3.0	0.134*	0.324*	0.459*
81-40096	1.25	0.012	0.017	0.017
	3.0	0.024	0.031	0.033*
82-40003	1.25	0.000	0.000	0.003
	3.0	0.010	0.010	0.014
82-40004	1.25	0.012	0.012	0.012
	3.0	0.011	0.011	0.011
82-40026	1.25	0.048*	0.105*	0.146*
	3.0	0.122*	0.208*	0.234*
82-40027	1.25	0.012	0.033	0.058*
	3.0	0.050*	0.115*	0.159*
82-40028	1.25	0.004	0.006	0.014
	3.0	0.013	0.031	0.055*
82-40029	1.25	0.002	0.004	0.009
	3.0	0.003	0.008	0.025
82-40031	1.25	0.007	0.018	0.047*
	3.0	0.022	0.093*	0.151*
82-40036	1.25	0.010	0.014	0.018
	3.0	0.019	0.027	0.047*

NOTE * = cracking observed.

TABLE 6. Results of Concrete Prism Expansion Test.

SAMPLE NUMBER	ALKALI CONTENT Na_2O%	EXPANSION OF CONCRETE PRISMS IN PERCENT		
		84 DAYS	168 DAYS	1 YEAR
82-40037	1.25	0.003	0.003	0.001
	3.0	0.006	0.006	0.016
82-40038	1.25	0.005	0.005	0.006
	3.0	0.005	0.005	0.005
82-40039	1.25	0.004	0.005	0.006
	3.0	0.005	0.012	0.028*
82-40040	1.25	0.001	0.001	0.001
	3.0	0.001	0.001	0.001
82-40043	1.25	0.001	0.001	0.002
	3.0	0.005	0.006	0.005
82-40044	1.25	0.002	0.002	0.003
	3.0	0.003	0.010	0.011
82-40045	1.25	0.005	0.006	0.008
	3.0	0.005	0.005	0.007
82-40046	1.25	0.009	0.019	0.029*
	3.0	0.019	0.036*	0.047*
82-40047	1.25	0.003	0.009	0.018
	3.0	0.012	0.037*	0.053*
83-9016	1.25	0.021	0.021	0.031*
	3.0	0.033*	0.042*	0.053*
83-40056	1.25	0.007	0.012	0.012
	3.0	0.010	0.014	0.016
83-40062	1.25	0.003	0.004	0.006
	3.0	0.007	0.009	0.044*[1]

NOTE * = cracking observed.
1 = slightly alkali-silica reactive, confirmed by mortar bar testing with 3% Na_2O cement and presence of alkali-silica gel.

TABLE 6. CONTINUED - Results of Concrete Prism Expansion Test.

Table 7: Suggested or actual specification requirements for the concrete prism expansion test to detect deleteriously expansive, alkali-carbonate reactive aggregate

AUTHOR	CEMENT OR ALKALI CONTENT AS Na_2O EQUIVALENT	MAXIMUM ALLOWABLE EXPANSION IN PERCENT
Swenson and Gillott (1964)	Not Stated	0.02 at 6 months
Smith (1964)	Greater than 1.1%	0.05 at 84 days but considered 0.02 might be more appropriate
Newlon et al (1972 a,b)	Job Cement or Equivalent	0.03 at 1 year 0.05 at 5 years
Smith (1974)	0.8 - 1.0%	0.02 at 84 days
CAN3-A23.1-M77 (1977) (Canadian Standards Association)	1.0%	0.03 at any age indicates potentially deleterious reactivity 0.02 at 3 months, wet exposure (Bridge Deck) 0.04 at 3 months, dry exposure
Walker (1978), ASTM draft proposal	Job Cement or Equivalent?	0.015 at 84 days 0.025 at 180 days 0.03 at 1 year
M.T.C. (1983) Draft Specification	1.25%	0.015 at 84 days 0.025 at 168 days
New, Proposed Limits (M.T.C.)	3.0% 1.25%	0.01 at 84 days or failing that, 1 year requirement 0.025 at 1 year

		SiO_2 Percent	Al_2O_3 Percent	Insoluble Residue Percent
Expansive Rock Cylinders (37) (>0.1% @ 4 weeks or > 0.2% @ 16 weeks)	Average	11.6	3.1	15.7
	Range	3.0-32	1.0-8.6	3.7-47
Non-Expansive Rock (79) Cylinders	Average	10.1	2.5	13.1
	Range	0.6-44	0.2-8.9	1.0-55
Expansive Concrete Prisms (7) (> 0.025% @ 1 year)	Average	7.5	2.2	10.7
	Range	2.8-10.1	0.7-3.0	2.2-15
Non-Expansive Concrete Prisms (19)	Average	7.3	1.9	9.5
	Range	2.4-19	0.5-4.4	2.3-24

Table 8. Summary of some chemical properties of alkali-carbonate expansive and non-expansive rocks and aggregates from Ontario.

LOCATION	SOURCE OF DATA	PERCENT ALKALIES as Na_2O	CONCRETE PRISM EXPANSION IN PERCENT			
			84 days	112 days	168 days	1 year
Pittsburg Quarry						
1st Lift (0-24')	This study	1.25	0.048	0.066	0.105	0.146
	Smith (1964) & Files	1.1	0.034	0.045	-	0.120
	Swenson & Gillott (1960)[1]	1.19	-	-	0.233	-
	Smith (1974)	0.8-1.0	0.023	0.027	0.039	0.055
1st Lift (0-24')	This study	3.0	0.122	0.152	0.208	0.234
	Smith (1974)	3.0	0.135	0.155	0.180	0.201
3rd Lift (36'-48')	This study	1.25	0.012	0.014	0.033	0.058
	Swenson & Gillott (1960)	1.19	-	-	0.058	0.070
	Smith (1964) & Files	1.1	0.013	0.015	-	0.034

Note 1: Expansion data reported by Swenson and Gillott may be for an aggregate equivalent to the "1957 production" of Smith (1964) who recorded an expansion of 0.092% at 84 days.

TABLE 9: Comparison of various concrete prism expansion test data reported for the Pittsburg Quarry near Kingston.

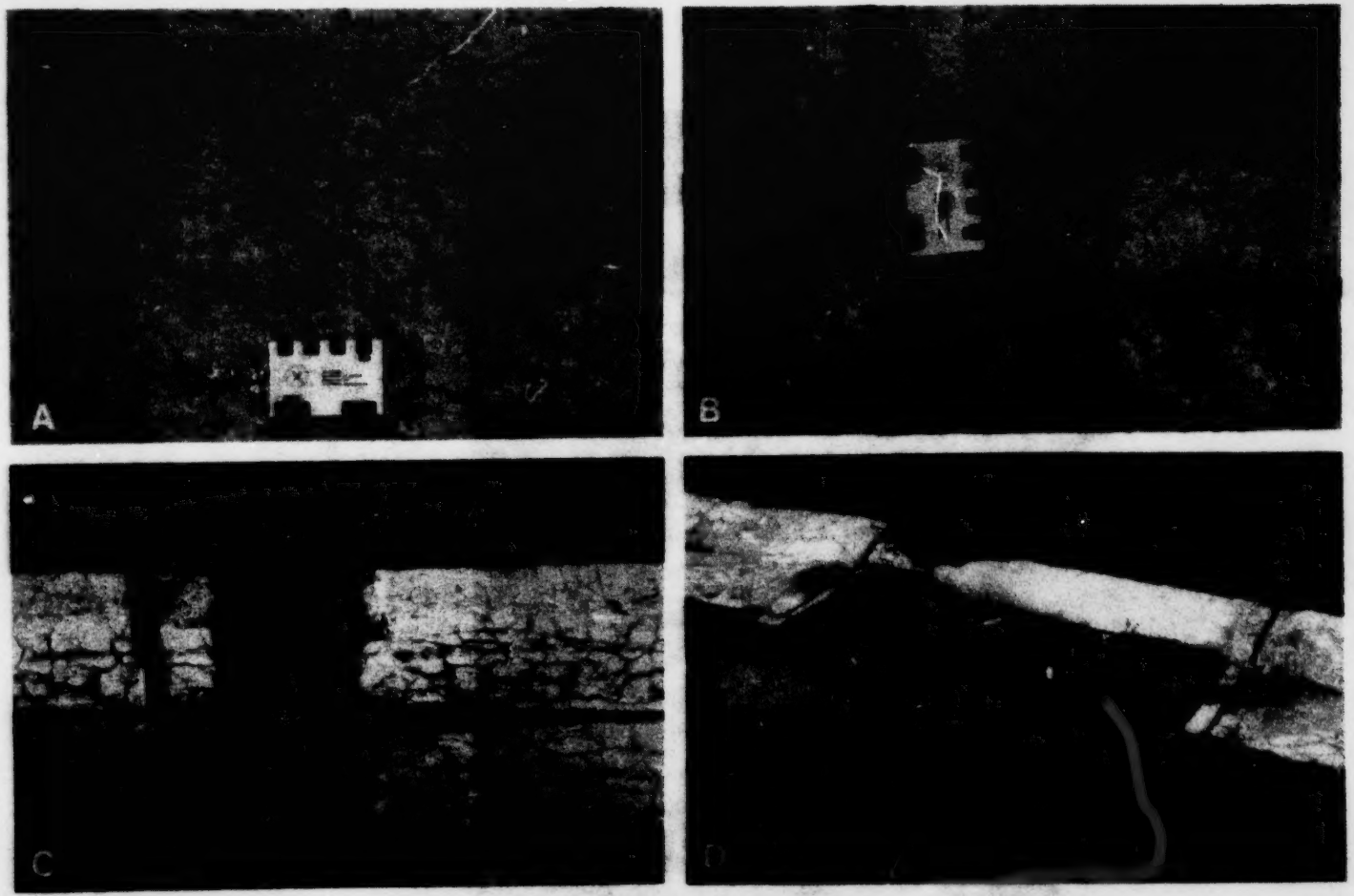


FIGURE 1. Effects of alkali-carbonate reaction near Cornwall, Ontario (Sample 81-40095). (A) General appearance of pattern cracking after 3 years. (B) Reactive concrete on right has moved 9 cm downwards compared to non-reactive concrete in left of photo, expansion of about 1.2% was recorded after 3 years. (C) Remedial measure taken to prevent further damage due to expansion was to provide asphaltic concrete expansion joints. (D) Damage to concrete and shoving of asphaltic concrete around catchbasin caused by expansion of reactive concrete after 3 years.

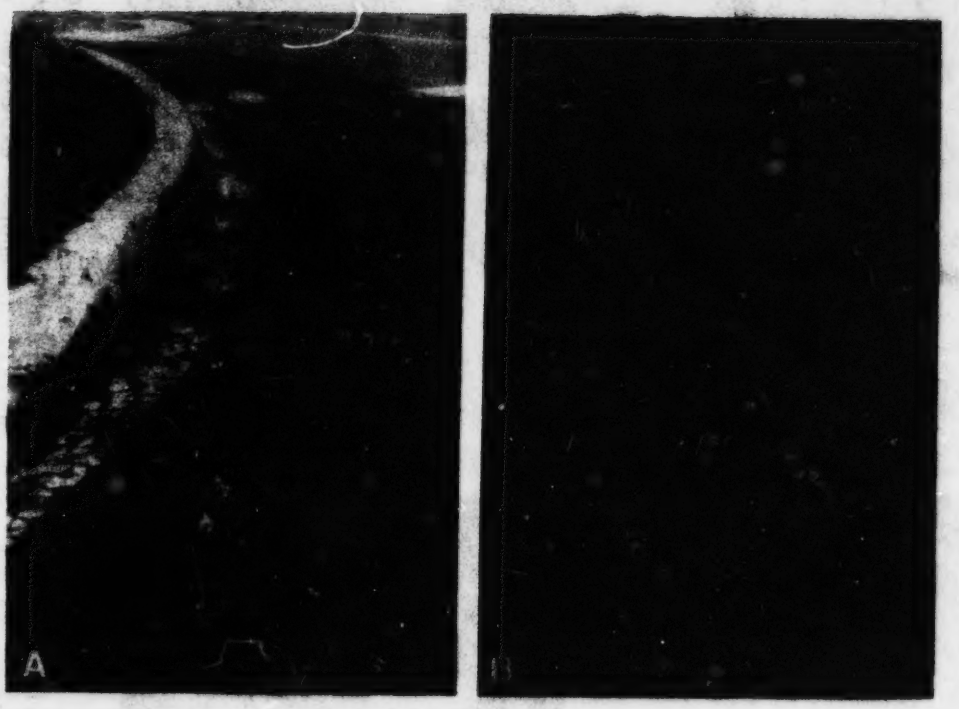


FIGURE 2. Effects of alkali-carbonate reaction near Cornwall, Ontario (Sample 81-40095). (A) Expansion of curb and gutter on a radius caused shoving and tension cracks in adjacent asphaltic concrete after 3 years. (B) Following crack development further damage due to frost action caused extensive deterioration after 5 years.

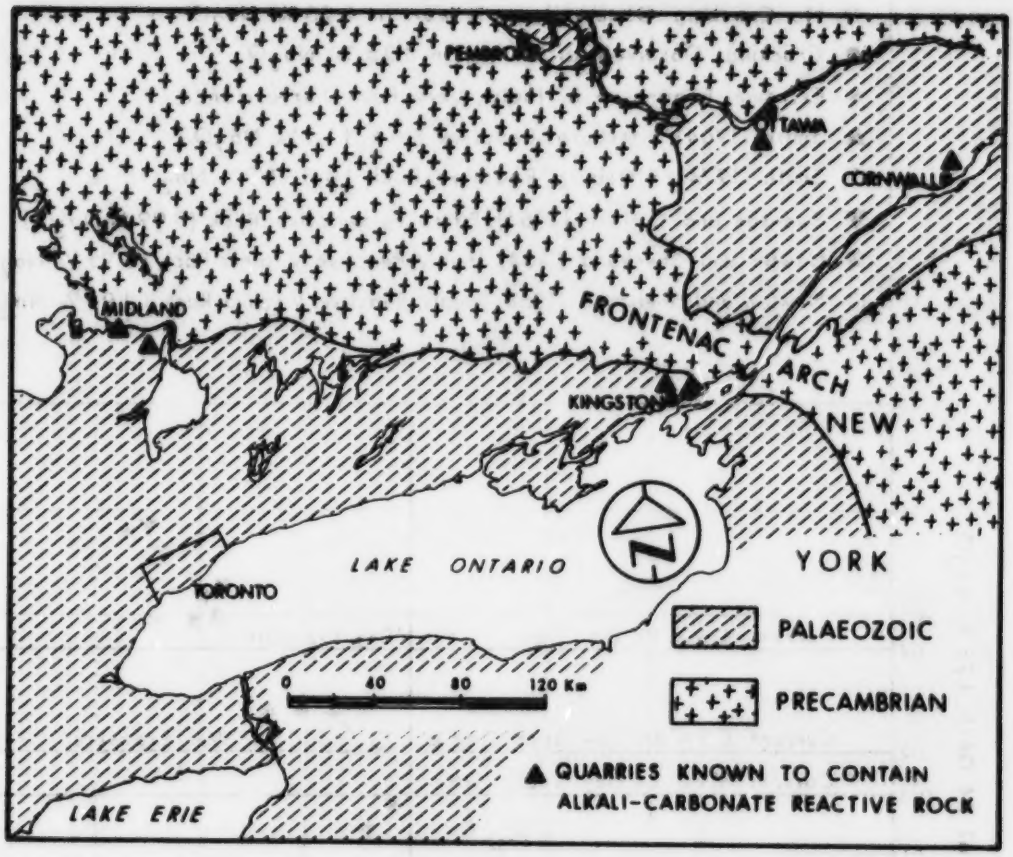


FIGURE 3. Location of quarries in Ontario known to contain alkali-carbonate reactive rock.

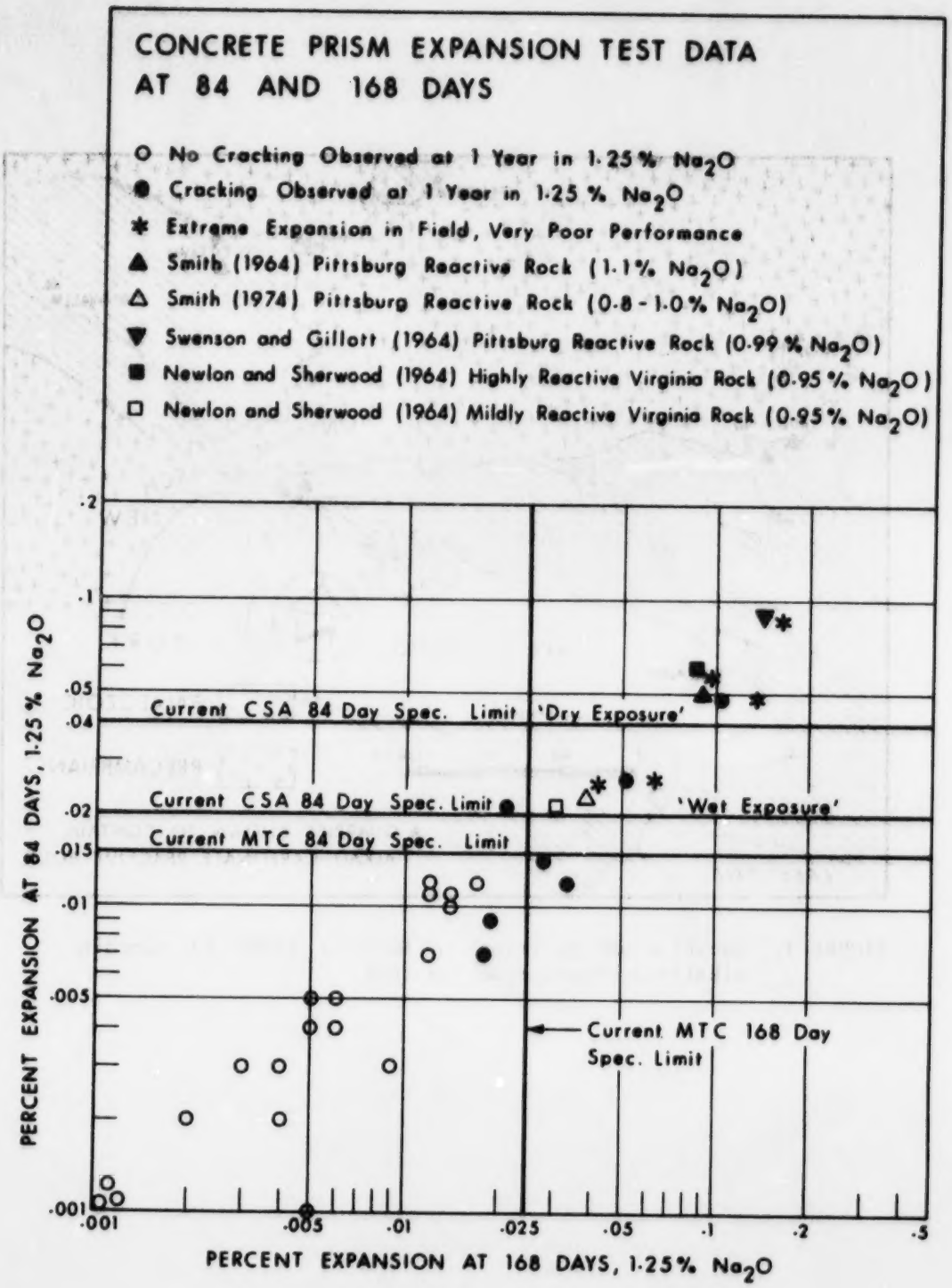

CONCRETE PRISM EXPANSION TEST DATA
AT 84 AND 168 DAYS
O No Cracking Observed at 1 Year in 1.25% Na2O
● Cracking Observed at 1 Year in 1.25 % Na2O
✱ Extreme Expansion in Field, Very Poor Performance
▲ Smith (1964) Pittsburg Reactive Rock (1.1% Na2O)
△ Smith (1974) Pittsburg Reactive Rock (0.8 - 1.0% Na2O)
▼ Swenson and Gillott (1964) Pittsburg Reactive Rock (0.99 % Na2O)
■ Newlon and Sherwood (1964) Highly Reactive Virginia Rock (0.95 % Na2O)
□ Newlon and Sherwood (1964) Mildly Reactive Virginia Rock (0.95% Na2O)
Current CSA 84 Day Spec. Limit 'Dry Exposure'
Current CSA 84 Day Spec. Limit
'Wet Exposure'
Current MTC 84 Day Spec. Limit
Current MTC 168 Day Spec. Limit
PERCENT EXPANSION AT 84 DAYS, 1.25 % Na2O
.2
.1
.05
.04
.02
.015
.01
.005
.001
.001
.005
.01
.025
.05
.1
.2
.5
PERCENT EXPANSION AT 168 DAYS, 1.25% Na2O

FIGURE 4

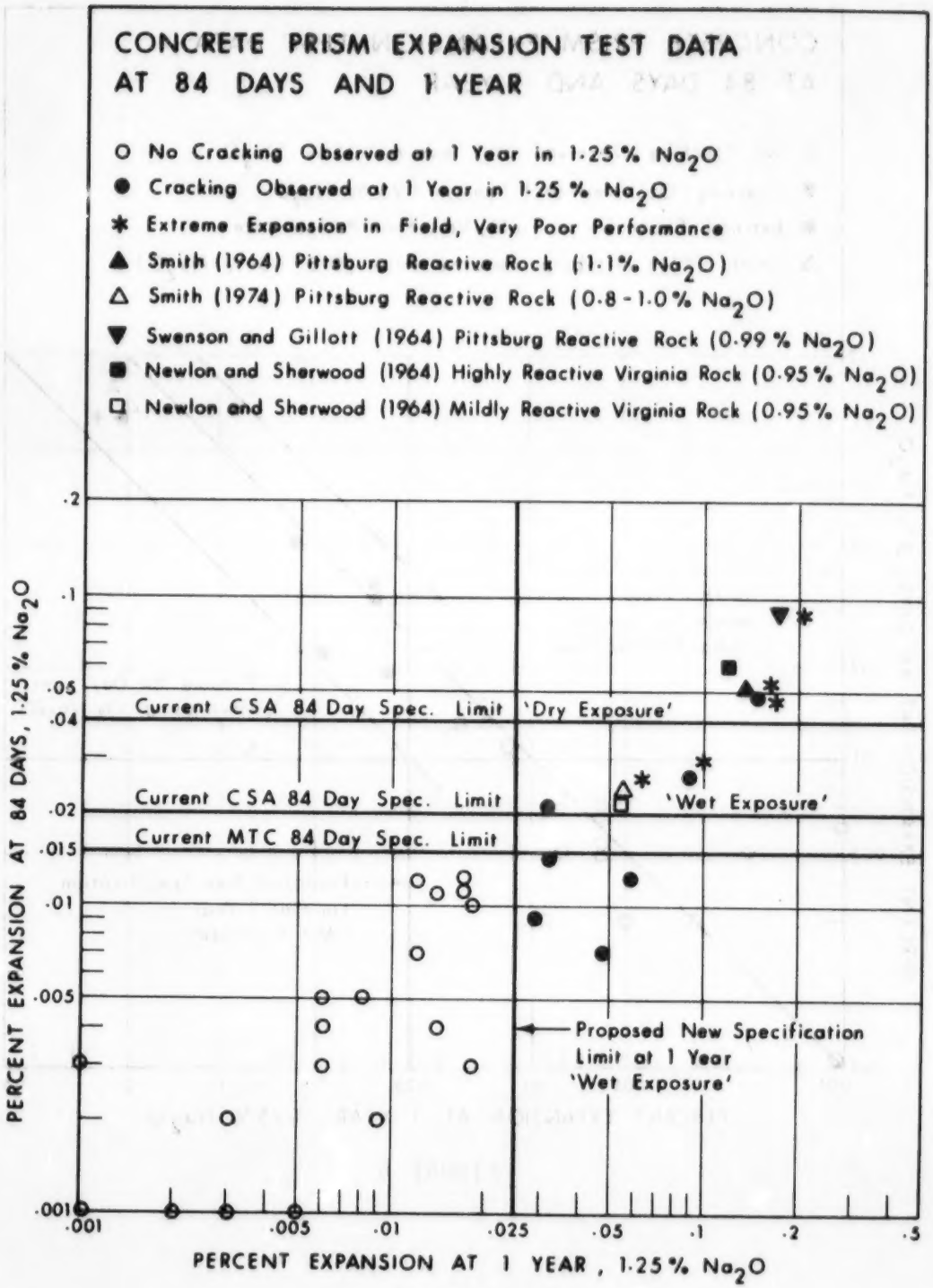

CONCRETE PRISM EXPANSION TEST DATA
AT 84 DAYS AND 1 YEAR
O No Cracking Observed at 1 Year in 1·25 % Na2O
● Cracking Observed at 1 Year in 1·25 % Na2O
✱ Extreme Expansion in Field, Very Poor Performance
▲ Smith (1964) Pittsburg Reactive Rock (1·1% Na2O)
△ Smith (1974) Pittsburg Reactive Rock (0·8 - 1·0 % Na2O)
▼ Swenson and Gillott (1964) Pittsburg Reactive Rock (0·99 % Na2O)
■ Newlon and Sherwood (1964) Highly Reactive Virginia Rock (0·95 % Na2O)
□ Newlon and Sherwood (1964) Mildly Reactive Virginia Rock (0·95 % Na2O)
Current CSA 84 Day Spec. Limit 'Dry Exposure'
Current CSA 84 Day Spec. Limit 'Wet Exposure'
Current MTC 84 Day Spec. Limit
Proposed New Specification Limit at 1 Year 'Wet Exposure'
PERCENT EXPANSION AT 84 DAYS, 1·25 % Na2O
.2
.1
.05
.04
.02
.015
.01
.005
.001
.001
.005
.01
.025
.05
.1
.2
.5
PERCENT EXPANSION AT 1 YEAR, 1·25 % Na2O

FIGURE 5

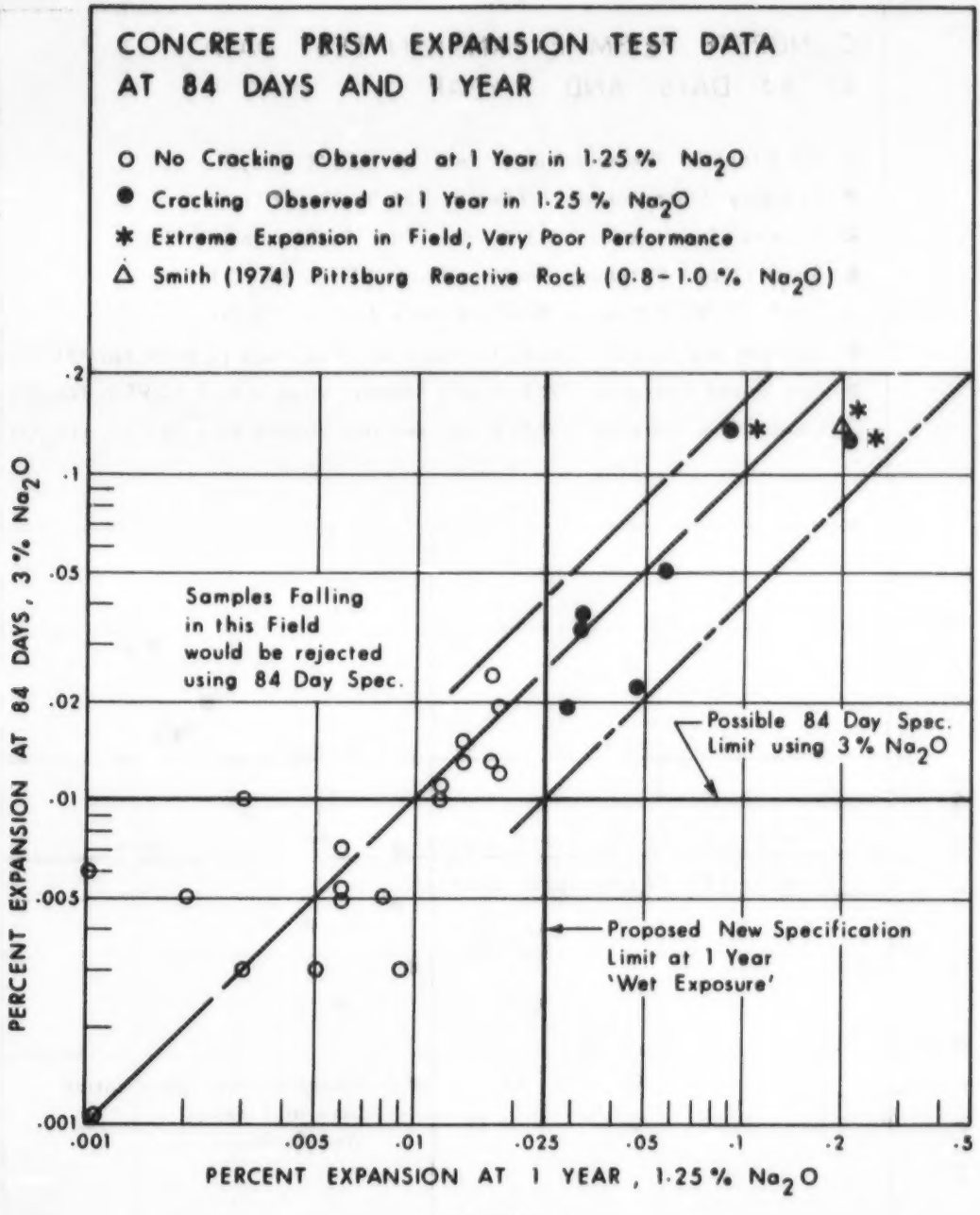

CONCRETE PRISM EXPANSION TEST DATA
AT 84 DAYS AND 1 YEAR
○ No Cracking Observed at 1 Year in 1.25 % Na_2O
● Cracking Observed at 1 Year in 1.25 % Na_2O
✱ Extreme Expansion in Field, Very Poor Performance
△ Smith (1974) Pittsburg Reactive Rock (0.8 - 1.0 % Na_2O)
Samples Falling in this Field would be rejected using 84 Day Spec.
Possible 84 Day Spec. Limit using 3 % Na_2O
Proposed New Specification Limit at 1 Year 'Wet Exposure'
PERCENT EXPANSION AT 84 DAYS, 3 % Na_2O
.2
.1
.05
.02
.01
.005
.001
.001
.005
.01
.025
.05
.1
.2
.5
PERCENT EXPANSION AT 1 YEAR, 1.25 % Na_2O

FIGURE 6

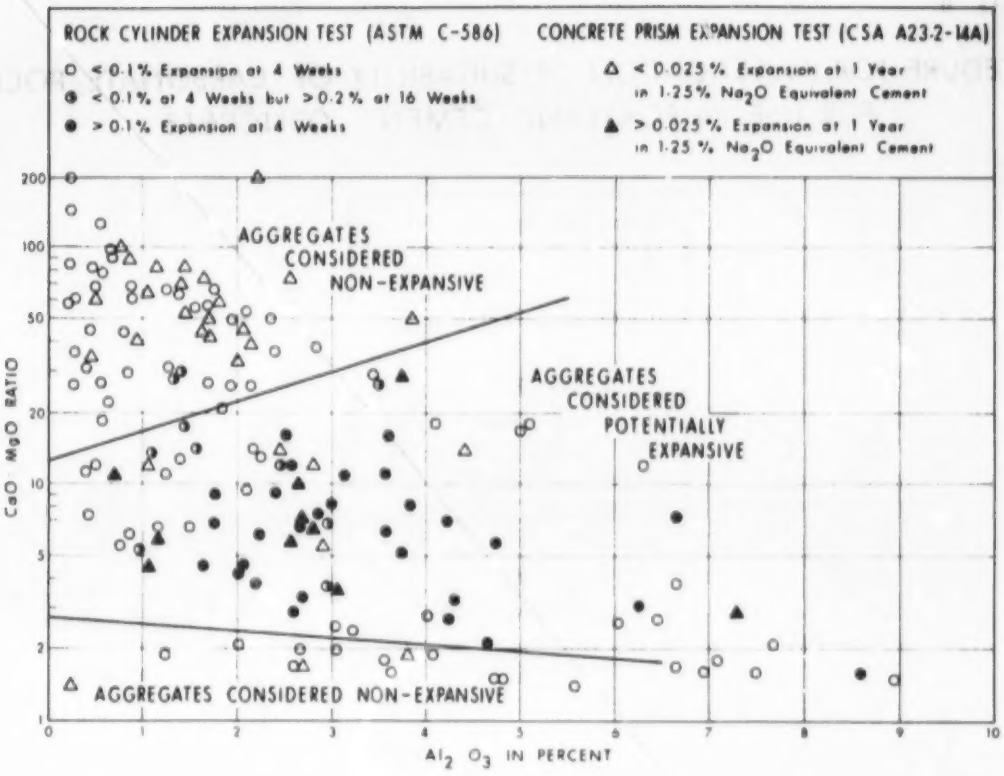


FIGURE 7

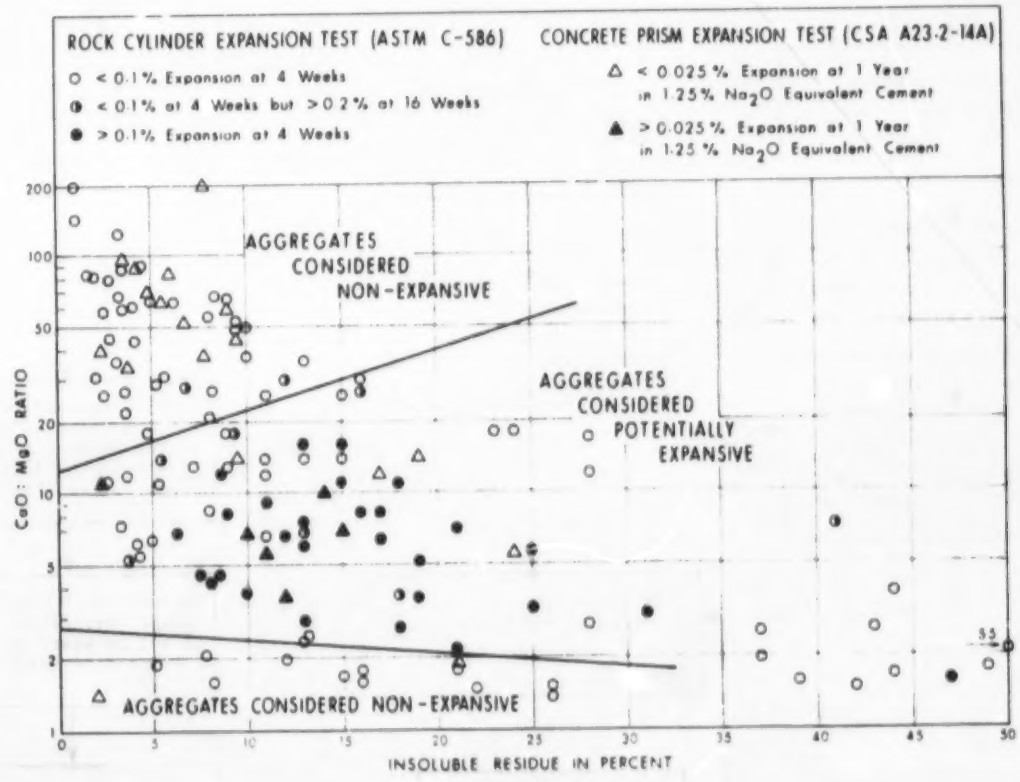
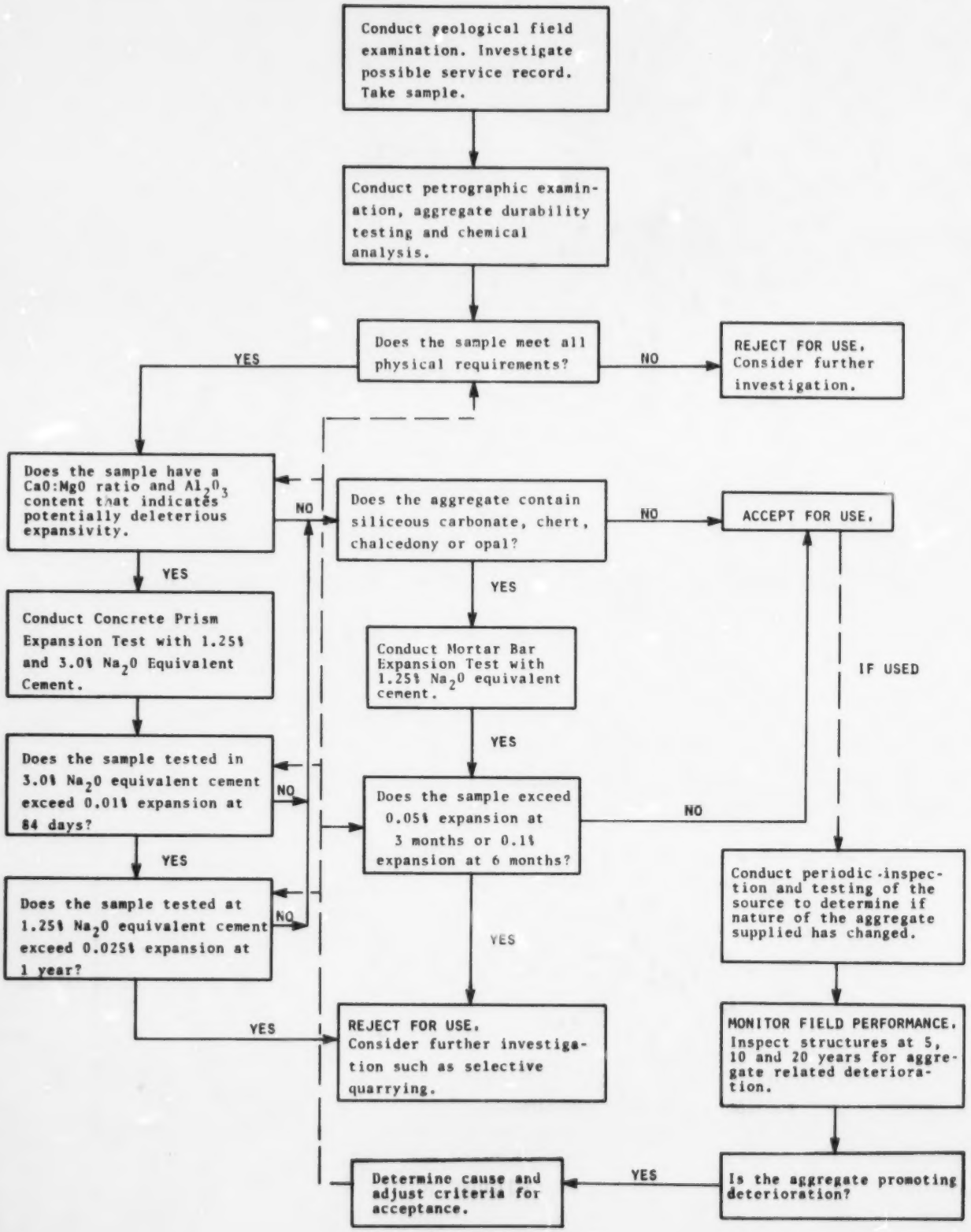


FIGURE 8

FIGURE 9

PROCEDURE FOR INVESTIGATION OF SUITABILITY OF CARBONATE ROCKS FOR USE IN PORTLAND CEMENT CONCRETE


Conduct geological field examination. Investigate possible service record. Take sample.
Conduct petrographic examination, aggregate durability testing and chemical analysis.
Does the sample meet all physical requirements?
YES
NO
REJECT FOR USE. Consider further investigation.
Does the sample have a CaO:MgO ratio and Al_2O_3 content that indicates potentially deleterious expansivity.
NO
YES
Does the aggregate contain siliceous carbonate, chert, chalcedony or opal?
NO
ACCEPT FOR USE.
YES
IF USED
Conduct Concrete Prism Expansion Test with 1.25% and 3.0% Na_2O Equivalent Cement.
Conduct Mortar Bar Expansion Test with 1.25% Na_2O equivalent cement.
YES
Does the sample tested in 3.0% Na_2O equivalent cement exceed 0.01% expansion at 84 days?
NO
YES
Does the sample exceed 0.05% expansion at 3 months or 0.1% expansion at 6 months?
NO
Does the sample tested at 1.25% Na_2O equivalent cement exceed 0.025% expansion at 1 year?
NO
YES
Conduct periodic inspection and testing of the source to determine if nature of the aggregate supplied has changed.
YES
REJECT FOR USE. Consider further investigation such as selective quarrying.
MONITOR FIELD PERFORMANCE. Inspect structures at 5, 10 and 20 years for aggregate related deterioration.
Is the aggregate promoting deterioration?
YES
Determine cause and adjust criteria for acceptance.

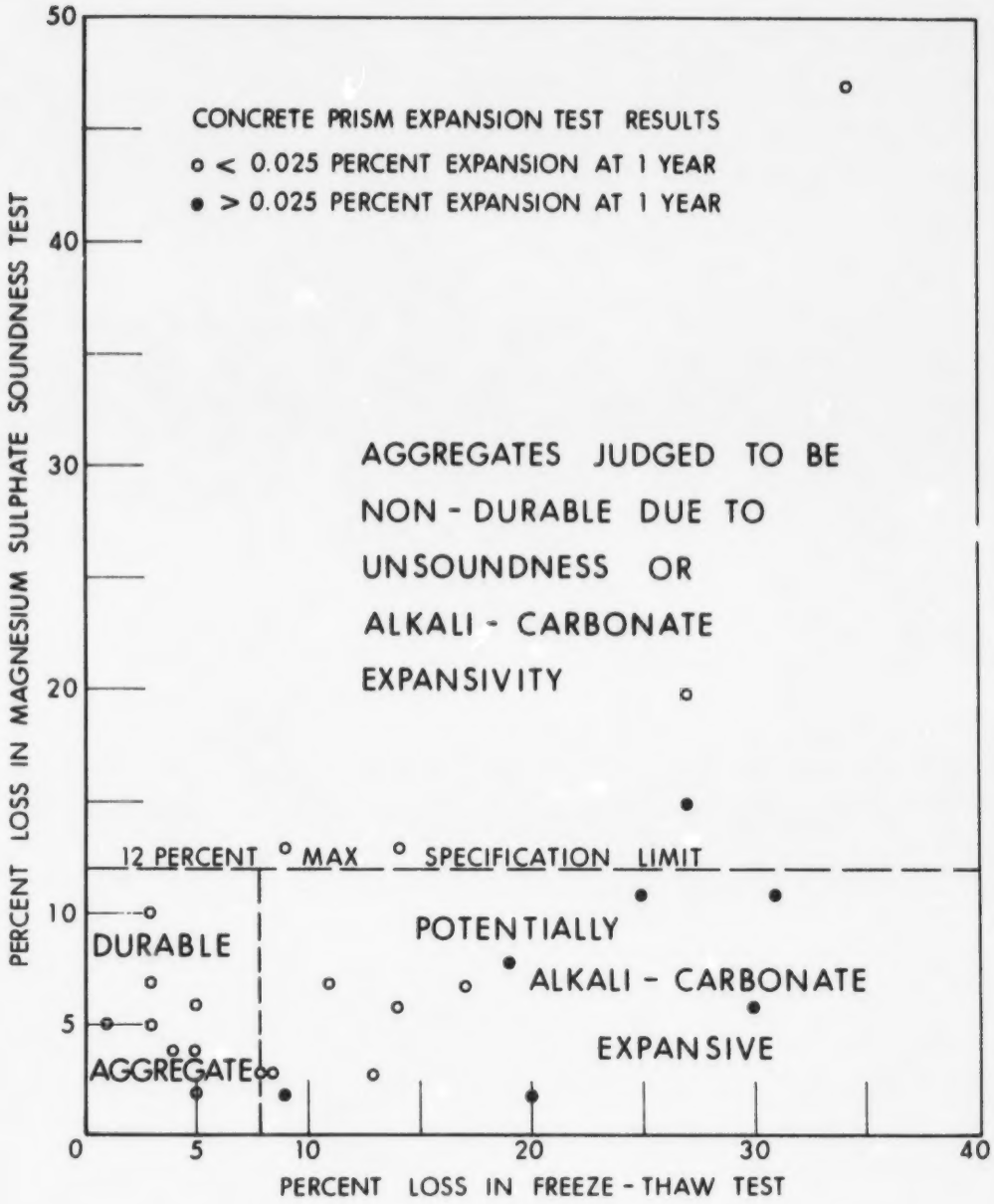

CONCRETE PRISM EXPANSION TEST RESULTS
o < 0.025 PERCENT EXPANSION AT 1 YEAR
• > 0.025 PERCENT EXPANSION AT 1 YEAR
AGGREGATES JUDGED TO BE NON-DURABLE DUE TO UNSOUNDNESS OR ALKALI-CARBONATE EXPANSIVITY
12 PERCENT MAX SPECIFICATION LIMIT
DURABLE AGGREGATE
POTENTIALLY ALKALI-CARBONATE EXPANSIVE
PERCENT LOSS IN MAGNESIUM SULPHATE SOUNDNESS TEST
PERCENT LOSS IN FREEZE-THAW TEST
0
5
10
20
30
40
50

FIGURE 10

APPENDIX

SUMMARY OF SAMPLE LOCATIONS AND FIELD PERFORMANCE

SAMPLE NUMBER	QUARRY NAME	N.T.S. MAP NAME	GRID REFERENCE	LEVEL IN QUARRY	REMARKS ON PERFORMANCE
81-40092	McLeod	Cornwall	200915	1st Lift 0 - 9.15 m	Satisfactory for over 30 years
81-40093	McLeod	Cornwall	200915	2nd Lift 9.15 - 17.4 m	Satisfactory for over 10 years
81-40094	McLeod	Cornwall	200915	3rd Lift 17.4 - 22.9 m	Causes cracking of moist concrete within 5 years
81-40095	McLeod	Cornwall	200915	4th Lift 22.9 - 28.1 m	Causes severe expansion and cracking of moist concrete within 3 years
81-40096	McLeod	Cornwall	200915	5th Lift 28.1 - 36.6 m	Not used due to poor durability
82-40003	Permanent	Cornwall	125880	1st Lift 0 - 6.1 m	Satisfactory for over 10 years
82-40004	Permanent	Cornwall	125880	2nd Lift 6.1 - 14.3 m	Never used but judged satisfactory
82-40026	Pittsburg	Gananoque	835020	1st Lift 0 - 7.3 m	Causes severe expansion and cracking (see Swenson, 1957)
82-40027	Pittsburg	Gananoque	835020	3rd Lift 11.0 - 14.6 m	Causes cracking of moist concrete
82-40028	Pittsburg	Gananoque	835020	4th Lift 14.6 - 20.7 m	Not used due to poor durability
82-40029	Permanent	Cornwall	125880	3rd Lift 14.3 - 24.1 m	Never used
82-40031	McFarland	Ottawa	365138	15.3 - 22.6 m	Causes cracking of precast concrete within 5 years
82-40036	McKendry	Sydenham	800072	0 - 10.1 m	Satisfactory
82-40037	Francon	Ottawa	558323	S. Qry 60 - 73 m, O.D.	Potentially alkali-silica reactive but not alkali-carbonate reactive
82-40038	Ranger	Alexandria	080220	2nd Lift 5.5 - 12.4 m	Satisfactory
82-40039	Bertrand	Hawkesbury	186490	2nd Lift 6.1 - 12.1 m	Satisfactory
82-40040	Long	Belleville	200017	0 - 5.9 m	Satisfactory apart from some shaley popouts

SAMPLE NUMBER	QUARRY NAME	N.T.S. MAP NAME	GRID REFERENCE	LEVEL IN QUARRY	REMARKS ON PERFORMANCE
82-40042	Blair	Winchester	840090	2nd Lift 4.6 - 12.8 m	Satisfactory
82-40043	Dufferin	Ottawa	358315	0 - 14.3 m	Satisfactory
82-40044	Deshenes	Ottawa	335315	1st Lift 0 - 9.2 m	Satisfactory for 14 years
82-40045	Custom	Sydenham	418058	0 - 6.0 m	Satisfactory
82-40046	Uhthoff	Orillia	195490	1st Lift 0 - 11.0 m	Causes cracking of moist concrete (see Ryell et al, 1974)
82-40047	Glen Lawrence	Gananoque	805045	1st Lift 0 - 14.0 m	Satisfactory
83-9016	Cook	Penetan-guishene	067585	1st Lift 0 - 4.5 m	Not known
83-40056	Francon	Ottawa	558323	S. Qry. 60 - 73 m O.D.	Due to fault, different rock from sample 82-40037
83-40062	Hoffman	Arnprior	905265	1st Lift 0 - 17.0 m	Satisfactory but slightly alkali-silica reactive at high alkali content (3% Na_2O)